research review

OFFICE of AEROSPACE RESEARCH

OAR: The Research Agency
of The United States Air Force

VOLUME VI NUMBER 9 SEPTEMBER 1967

flow & heat-transfer phenomena of plasma arcs magnetically balanced in a cross flow

DR. WARD C. ROMAN, Thermomechanics Research Laboratory, ARL

Although more than 60 years of research in plasma-arc phenomena have greatly advanced our knowledge of the plasma-arc discharge, the understanding of the basic energy-exchange and conversion processes between plasma arcs, electrodes, gas flow, and magnetic fields is still not sufficient to permit the design of plasma-arc devices compatible with the requirements of today's aerospace technology. Through its thermal and magnetic properties, the plasma arc finds many applications in aerospace systems. Recently, the application of plasma arcs as heating devices for re-entry simulation tunnels, crossed-field accelerators, space propulsion engines, and high-intensity radiation generators, has focused renewed attention on the need for a better understanding of the complex interaction phenomena involved. To gain this better understanding, a different approach was recently taken at the Thermomechanics Research Laboratory of ARL (1). Information obtained from previous studies at this Laboratory of plasma-arc columns moving at very high speed along electrodes indicated a drastic change in the arc-column size, shape, length, and voltage gradient, therefore making it very difficult to correlate the arc column to a known aerodynamic shape (2). In addition, detailed diagnostic investigations of rapidly moving arcs require difficult transient techniques.

Thus, instead of studying moving arcs in stagnant gas, as the majority of previous investigators have done, a stationary plasma arc, held balanced magnetically in a transverse moving gas stream was investigated. In this case, the Lorentz forces generated by the external magnetic field were adjusted to balance the aerodynamic "drag" of the plasma-arc column.

This article describes the results of an experimental study made on the central 2-inch portion of a vertical plasma-arc column of 200 to 400 amperes, which was held balanced magnetically in an atmospheric pressure, cross-flow air stream at velocities up to 60 ft/sec. The arc column was held stationary against the flow by magnetic fields up to 50 gauss provided by an iron-core electromagnet. The experiments were conducted under steady-state flow conditions with aver-

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age run times of 1 hour. A schematic drawing of the open jet facility is shown in Figure 1. The cathode was a cylinder of 1/4-inch diameter made of 2% thoriated tungsten. A gas injector surrounded the cathode, and provided a small amount of argon gas to prevent rapid oxidation of the cathode. The anode was a helical coil of copper tubing of 1/4-inch outside diameter. This water-cooled coil was wound so that the arc interaction with the magnetic field produced by the current in the coil drove the anode attachment spots rapidly over the surface to spread the high heat load. The test region of the arc column was separated by water-cooled electrically floating copper locators which also served as alignment reference points.

The arc power was supplied by two d-c power supplies, each capable of 125-kw output. The 4-inch-diameter pole caps of the

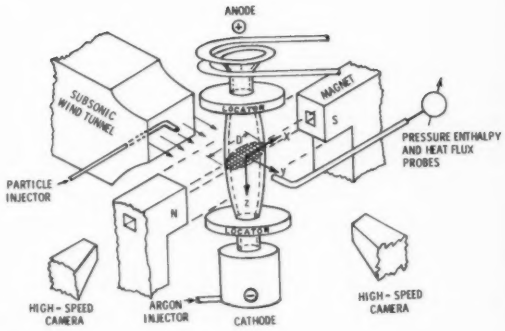

Figure 1.
Magnetically balanced plasma arc in cross flow.

electromagnet were shaped to provide a slightly increasing field (about 5%/inch) in the downstream direction. A 3/8-inch-diameter hole along the axis of the pole pieces permitted viewing the arc column when it was

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OAR RESEARCH REVIEW is published monthly by the Office of Scientific and Technical Information (RRYC), Hq Office of Aerospace Research, USAF, 1400 Wilson Boulevard, Arlington, Va. 22209. The objective of this publication is to make a positive contribution to the exchange of information concerning Air Force conducted and sponsored research activities.

JACOB SEIDEN
Editor

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in the balanced vertical position.

Several different types of diagnostic equipment were used. A 7,000 frames/sec Fastax camera was used for the flow visualization studies. A water-cooled calorimetric probe was used both to measure the specific total enthalpy in the arc wake and as a stagnation pressure probe (3). The distribution of heat flux and relative turbulence level in the wake was measured by a water-cooled hot-wire probe (4). The potential gradient of the arc column was determined both from measurement of the potential difference between the top and bottom locators (see Figure 1) and from measurement with separate tantalum potential probes. The total radiation dissipated to the surroundings of the arc column was measured with a calibrated radiometer.

One of the most interesting results of the tests was the measurement of the representative arc dimension transverse to the flow and parallel to it. It was found that the representative dimension increased in the direction transverse to the flow axis and decreased in the direction parallel to the flow as the transverse blowing velocity and corresponding external magnetic-field strength increased. Thus, the arc cross-sectional shape changed from an initially circular geometry to a flattened, approximately elliptical geometry with the major axis perpendicular to the flow direction (see Figure 1). In addition, the arc column behaved like a solid aerodynamic drag body, impervious to the gas flow. The magnetic-field strength necessary to balance the arc against the cross flow was found to be proportional to the square of the transverse blowing velocity. Note that this dependence is the same as that obtained by equating the aerodynamic drag force and magnetic retarding force on a solid conducting cylinder of unit length: $BI = (1/2)\,\rho\, C_D D\, V_\infty{}^2$. The calculated drag coefficients, when based on the actual arc dimensions, were in close agreement with those of solid cylinders. Figure 2 shows the variation of this analogous drag coefficient with the Reynolds number. Figure 3 shows qualitatively a velocity profile as measured in a plane 1/4-inch behind the arc column. Also

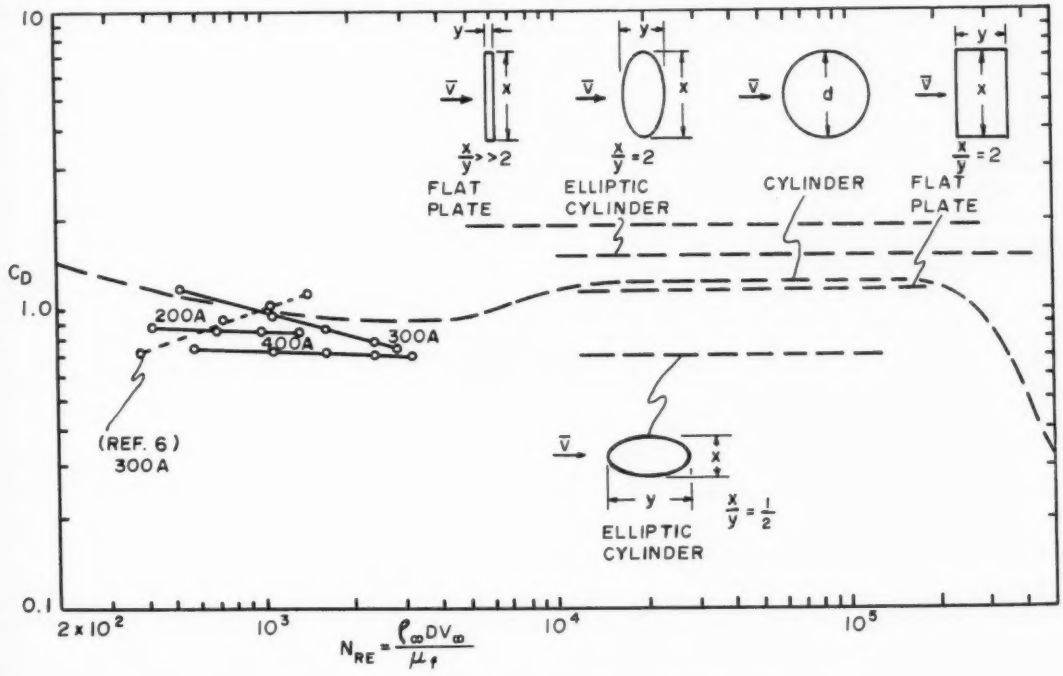

Figure 2. Variation of drag coefficient with Reynolds number.

shown are some boundaries of the wake as functions of the arc current and, for comparison, the wake boundary of an unheated solid cylinder of equivalent dimension. The measured shape of the arc wake was also verified by injecting spherical aluminum particles (2 to 20 microns) through a probe of 1/16-inch outside diameter located slightly upstream of the arc column (see Figure 1). The probe could be traversed in a horizontal plane across the center of the blowing nozzle. The particle vapor trails in the wake region were photographed with high-speed cameras. The photographs showed wake-boundary symmetry and vortex shedding from the inner side of the arc wake boundary. Vortex shedding and a high degree of turbulence were measured with the water-cooled hot-wire probe in the flow layers in the immediate vicinity of the wake boundaries. This vortex-shedding frequency was comparable to bluff bodies in a similar flow field.

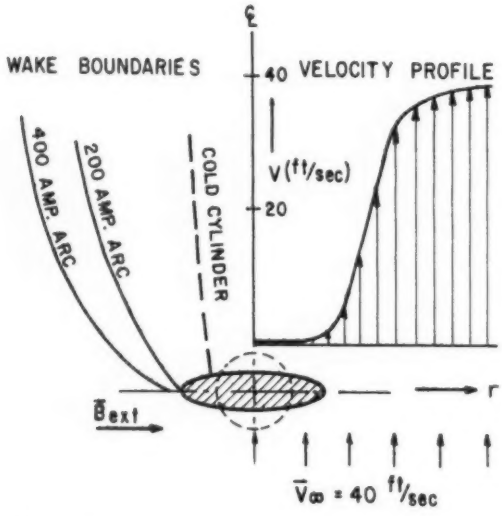

Figure 3.
Velocity field behind balanced plasma arc.

The results of an over-all energy balance on the system indicated that the additional electrical power required for the arc in cross flow as compared to the no-blowing case was transferred almost completely to the transverse gas flow. This represented a small percentage of the over-all arc power; e.g., the energy balance for the 300-ampere

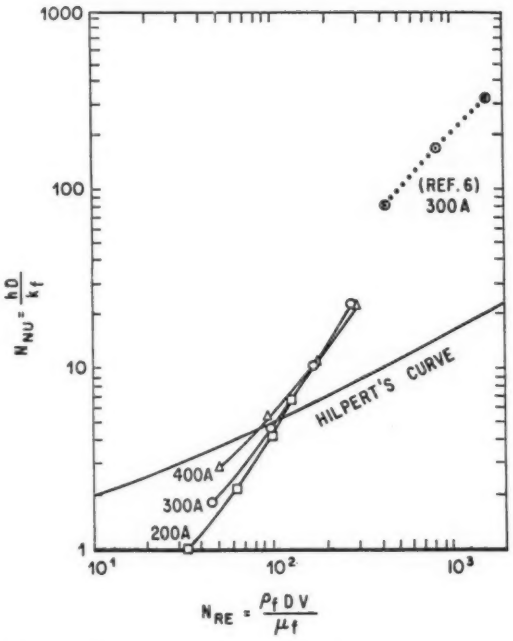

Figure 4.
Plot of Nusselt number vs. Reynolds number.

arc with a cross-flow velocity of 42 ft/sec indicated that only 4% of the total power input was transferred to the cross flow and was measured in the arc wake. If the analogy between an arc in transverse flow and a solid cylindrical heated body in cross flow may be extended to the heat-transfer process from the arc to the flow field, a heat-transfer coefficient may be defined as $N_{Nu} = hD/k_f$, where h is the convective heat-transfer coefficient, D is the significant dimension, and k_f is the thermal conductivity evaluated at the film temperature. Its relationship to the Reynolds number is shown in Figure 4. Also shown is Hilpert's analogous relationship for solid heated cylinders in cross flow (5). However, caution must be exercised in comparing the results of heated solid bodies with the results of plasma arcs. In the former, the temperature difference between the body surface and the free stream is relatively small, whereas in the latter, it is at least an order of magnitude greater.

From the reported measurements of the energy distribution in the wake of an arc it appears that, in many aspects, a plasma-arc

column in transverse flow may be compared to a highly heated solid cylinder of comparable dimension and temperature. This analogy applies specifically to the thermofluiddynamics of the wake, and may be used to explain qualitatively many of the results obtained, including the arc column's imperviousness to the incoming transverse gas flow. However, a full explanation of this behavior and of the change of shape of the arc cross section will require a detailed investigation of the yet-unknown hydromagnetic flow phenomena within the arc column. Only then can the validity and limitations of this analogy model be accepted. Corresponding research is in preparation at the Thermomechanics Research Laboratory.

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Dr. Ward C. Roman, a research scientist with the Thermomechanics Research Laboratory, ARL, has been working primarily in the field of magnetohydrodynamics, investigating problems in plasma-arc technology. At present, he is conducting research in high-pressure, high-current plasma arcs under the influence of transverse external magnetic fields and aerodynamic flow.

Dr. Roman received the Bachelor of Mechanical Engineering degree from Rensselaer Polytechnic Institute in 1958. The Ohio State University awarded him the M.S. and Ph.D. degrees in Mechanical Engineering in 1962 and 1966, respectively. Commissioned a second lieutenant in the Air Force upon his graduation from R.P.I. in June 1958, he joined ARL upon his release from extended active duty in June 1962 as a Task Scientist. He is a member of Pi Tau Sigma and Sigma Xi.

THE DEFECT STRUCTURE OF METAL OXIDES

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The return of metals to more stable compounds by the processes of oxidation and corrosion is of constant concern in all engineering applications. In many cases, fortunately, the oxidation (or corrosion) is retarded by the oxidation products which separate the metal from the oxidizing atmosphere. Catastrophic oxidation generally results if the oxidation products are not effective in at least partially protecting the metal. Many of the refractory metals fail in a catastrophic fashion which seriously limits their use. Molybdenum and tungsten form volatile oxides while niobium (columbium) pentoxide spalls extensively, resulting in a rapid oxidation rate that is independent of time. This is in contrast to the protective oxide (parabolic) case (e.g., Fe_xO) wherein

the oxidation rate decreases as the oxide becomes thicker.

Since in parabolic oxidation the metal is separated from the oxidizing atmosphere by a continuous solid oxide, it is clear that the retarded oxidation must proceed by the migration of ions through the lattice of the oxide. The transport and, hence, the oxidation rate, depend on the type, number and

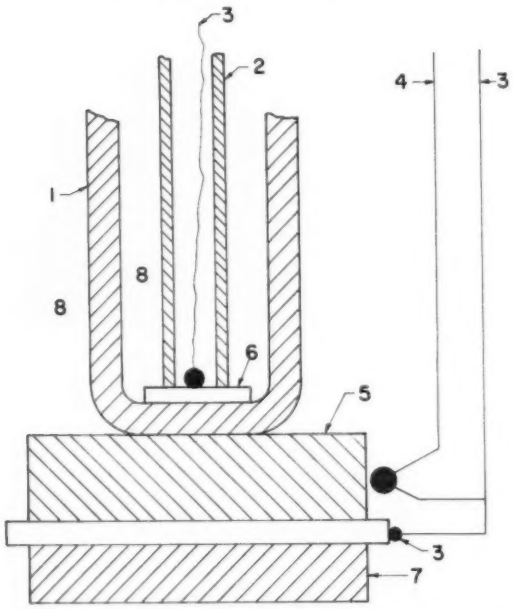

Figure 1. Schematic of cell holder: (1) 7.5 weight percent CaO-stabilized zirconia; (2) alumina insulator; (3) Pt contacts; (4) Pt-PtRh thermocouple; (5) Fe-Fe$_x$O reference electrode; (6) wustite sample; (7) alumina thrust block; and (8) static vacuum.

mobility of ionic defects in the oxide. Since the defect structure of oxides can be modified, it should be possible, in principle, to design alloys with lower parabolic oxidation rates. Unfortunately, the study of the defect structure of oxides is quite difficult. A new technique, solid-state coulometric titration, is being applied at ARL to study the defect structure of transition-metal oxides with the goal of understanding the relatively great differences in the protective nature of these oxides and to predict effective methods to increase oxidation resistance.

The titration technique is based on the use of calcia-stabilized zirconia galvanic cells (see Fig. 1). Early emf experiments of this type involved a measurement of a difference in oxygen activity between a two-phase electrode and a reference electrode. This type of cell has been used with great success for highly accurate measurements of the standard free energy-of-formation of oxides (e.g., 1) and for the accurate determination of activities in alloy systems (e.g., 2). Measurements have also been attempted using cells consisting of a reference electrode and a single-phase electrode of known oxygen content. Ksenofontova et al (3) used this arrangement to study the stability ranges and activities in tungsten oxides. Wilder (4) similarly determined the activity of oxygen in a number of liquid copper solutions.

An obvious extension of this type of measurement is the solid-state coulometric titration of oxygen. By this technique the composition of a single-phase electrode can be changed at the experimental temperature by permitting and monitoring a current flow in the external electrical circuit. A smaller-than-equilibrium imposed emf will permit a mass transport of oxygen through the electrolyte between the sample and reference electrode in the spontaneous direction. A larger-than-equilibrium emf will reverse the direction of oxygen transport. If the transport number for oxygen ions in the electrolyte is known, the changing oxygen content of the sample can be easily related to the quantity of charge passed by the application of Faraday's Law. The conductivity of calcia-stabilized zirconia has been shown to be essentially anionic in the temperature and oxygen partial-pressure range of this investigation.

Although the defect structures of the refractory metal oxides are of primary interest, an initial series of experiments on wustite (Fe$_x$O) was undertaken to check the method. Wustite was selected because of the wealth of existing data, the rapid attainment of equilibrium, and because the oxygen partial pressures in equilibrium with wustite closely approximate those of the

tungsten oxides. The results of these experiments were internally consistent and in excellent agreement with those of most earlier investigators. As an example, Fig. 2 shows the variation of oxygen content of

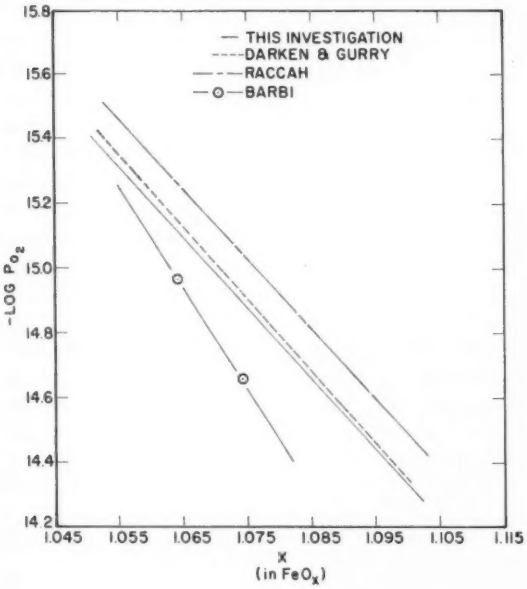

Figure 2. Log P_{O_2} vs composition at 965°C.

wustite, x, with oxygen partial pressure as determined by various investigators. The results further indicate that the postulated unassociated divalent iron vacancy-electron hole-defect type is not valid for wustite. More important, however, is the demonstration of the applicability of the emf technique. As has been pointed out before, the accuracy possible with the emf method is inherently greater than with gas equilibration methods. The biggest advantage of titration, however, is the ability to change the composition by a minute amount and simultaneously measure the associated oxygen activity. A simple calculation shows that the change in composition that can be detected coulometrically is many orders of magnitude smaller than that which can be detected gravimetrically. This technique makes possible the study of the compositions and defect structures of oxides hitherto considered stoichiometric.

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1st Lt Frank E. Rizzo has been a research metallurgist with the Metallurgy and Ceramics Research Laboratory, ARL, since September 1964. He was graduated from the University of Detroit with a B.Ch.E. in 1961. In August of that year, he was commissioned a second lieutenant in the Air Force Reserve and granted a delay from active duty to permit him to continue his education. As a graduate student from September 1961 to August 1964, Lt. Rizzo was successively a teaching fellow, acting instructor, and instructor in metallurgical engineering at the University of Cincinnati, earning his M.S. in 1963 and his Ph.D. in 1964 at that same University. He is a member of the American Society for Metals and the Metallurgical Society of AIME.

microwave rectification and mixing using piezoelectric media

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Dr. Paul H. Carr is a solid-state physicist with the Microwave Physics Laboratory, AFCRL, engaged in research on the generation of microwave phonons and on their interaction with each other (phonon-phonon scattering) and with magnetic materials. He received both his B. S. in Physics (1957) and M. S. in Physics (1961) from M.I.T., and his Ph. D. in Physics (1966) from Brandeis University. He has done research at the Lincoln Laboratory on the galvomagnetic effects in semiconductors and in magnetic transition in Ti_2O_3 and V_2O_3. On active duty as an officer at the Army Missile Command Calibration Center, he worked on a new technique for the calibration of accelerometers, infrared and optical detectors, and vacuum gauges. Dr. Carr is a member of the American Physical Society and Sigma Xi. He has about 10 research papers to his credit.

It is well known that the square of a sinusoidally varying function contains both a second harmonic and a static component. Previous experiments at AFCRL dealing with nonlinear microwave acoustics (microwave phonons) have detected the second harmonic. The apparatus shown in Fig. 1 has recently been used for detecting the static component, or equivalently for rectifying microwave energy. The ~ 3 GHz reentrant cavity concentrates the microwave electric field across the ~ 0.1-mm-thick quartz disc, whose fundamental acoustic frequency is ~ 29 MHz. A d-c voltage is produced across the piezoelectric quartz disc by the radiation pressure, nonlinearities in the material coefficients, and thermal effects. The voltage is detected by amplitude modulating the microwave input. The modulation envelope of the "static" voltage across the disc is similar to that of the microwaves, and this voltage is capacitively coupled to the two insulated halves of the cavity, where it is measured. The rectified voltage is largest when optically polished X-cut discs are excited at an overtone acoustic-resonance frequency (see Fig. 2). This occurs when the frequency of the cavity is an odd multiple of the fundamental acoustic frequency of the disc.

The top part of Fig. 3 shows an oscillogram of the pulse-modulated "static" voltage across a polished X-cut quartz disc on acoustic resonance. The microwave power exciting the cavity is about 1 w. In the bottom part of the figure, the microwave power to the cavity is detected by a conventional semiconducting diode. Although the signal-to-noise ratio of the quartz disc for 1 w of power dissipated in the cavity is less than that of the diode, the quartz does have the advantage of being almost "burnout proof." Its power-handling capacity is mainly limited by electrical breakdown across the electrodes of the reentrant cavity, which occurs when ~ 100 w of microwave power are dissipated in the cavity. The maximum burnout rating of semiconducting diodes is ~ 10 ergs. The ~ 30 ergs of energy absorbed by the quartz crystal for the pulse in Fig. 2 would have burned out the semiconducting diode. Indeed, a microwave attenuator was used in front of the

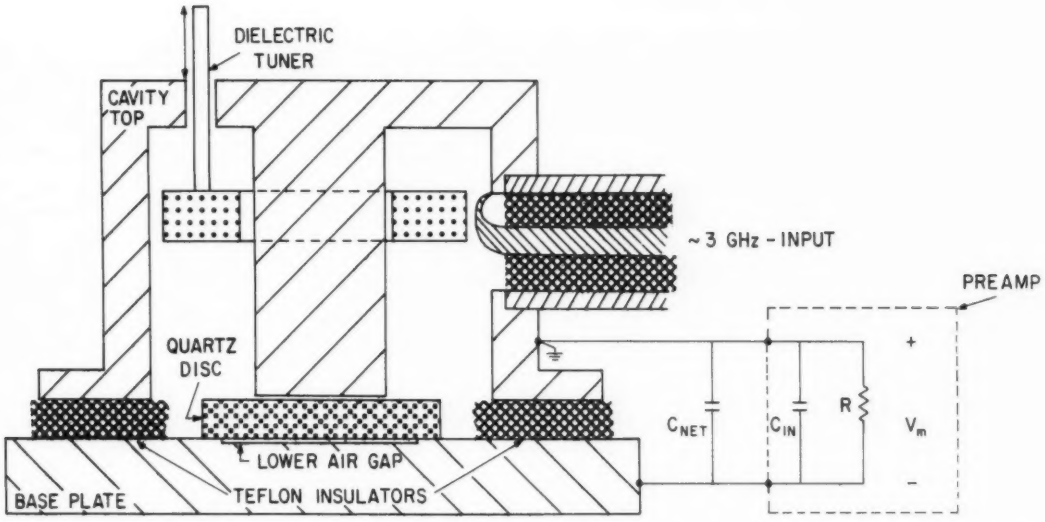

Figure 1. Cross-sectional diagram of the ~ 3-GHz re-entrant microwave cavity used to excite the piezoelectric quartz disc, and schematic diagram of the electrical circuit used to detect the quasistatic voltage across the disc.

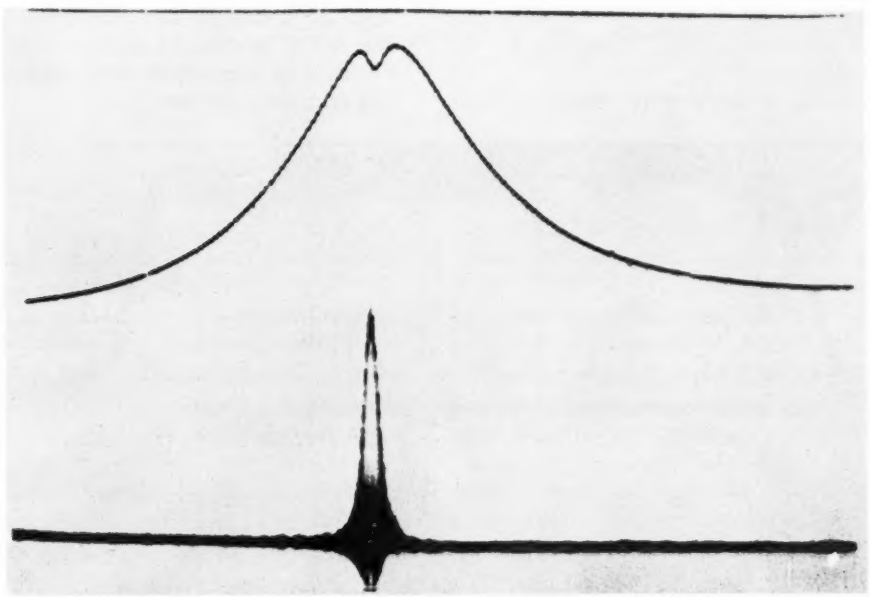

Figure 2. (Top) Zero reflected power line for center trace.
(Center) Microwave power reflected from the cavity (vertical scale) as a function of frequency (horizontal scale). The small, narrow acoustic resonance ($Q_{ac} \approx 6000$) is observed whenever the broad cavity resonance ($Q_o \approx 400$) is tuned to an odd multiple of the ~ 29-MHz fundamental acoustic resonance of the disc.
(Bottom) Envelope of the ~ 50-Hz amplitude-modulated quasistatic voltage across the disc as a function of frequency, showing that the maximum voltage is observed on acoustic resonance.

semiconducting diode to prevent this.

On acoustic resonance, the dominant nonlinearity is the strain dependence of the piezolectric constant of the disc. Off acoustic resonance, a much smaller output was observed. A theoretical analysis showed that the magnitude of the voltage was mainly produced by the radiation pressure or Maxwell-Faraday stress.

The frequency dependence of the output is related to the surface quality of the quartz. When discs were used with surfaces much rougher than the 2 μ sonic wavelength of the phonons, no acoustic resonance was observed. This property is useful for broad-band applications. The inherent high Q associated with rectification at overtone acoustic-resonance frequencies in polished piezolectric discs may also be useful for frequency-control applications. The rectified output is directly proportional to the microwave power. Therefore, a square-law detector is available which exhibits an inherently high Q or an essentially flat frequency response, depending on the surface of the material.

The mixing of microwave energy by nonlinearities in the excitation of the disc is observed in the following manner. When the relatively low-Q re-entrant cavity was excited by two separate microwave sources, a maximum output was observed when the difference in the frequencies of the two sources was equal to the fundamental resonant frequency of the disc. This behavior is illustrated in Fig. 4. Here the frequency of one microwave source is held constant while the frequency of the second source is modulated. The maximum peak-to-peak voltage output (vertical scale) is observed when the difference frequency (horizontal scale) is equal to 29 MHz, the fundamental acoustic resonant frequency of the disc. The bandwidth has been observed to vary between 10 to 40 kHz. This type of mixer is very attractive for mixing at higher-power levels than is now possible with presently available semiconducting diodes, which have relatively low burnout ratings. Piezoelectric mixers may also be of use in high-power radar systems where, at present, elaborate switches must be used to prevent the semiconducting mixers from burning out.

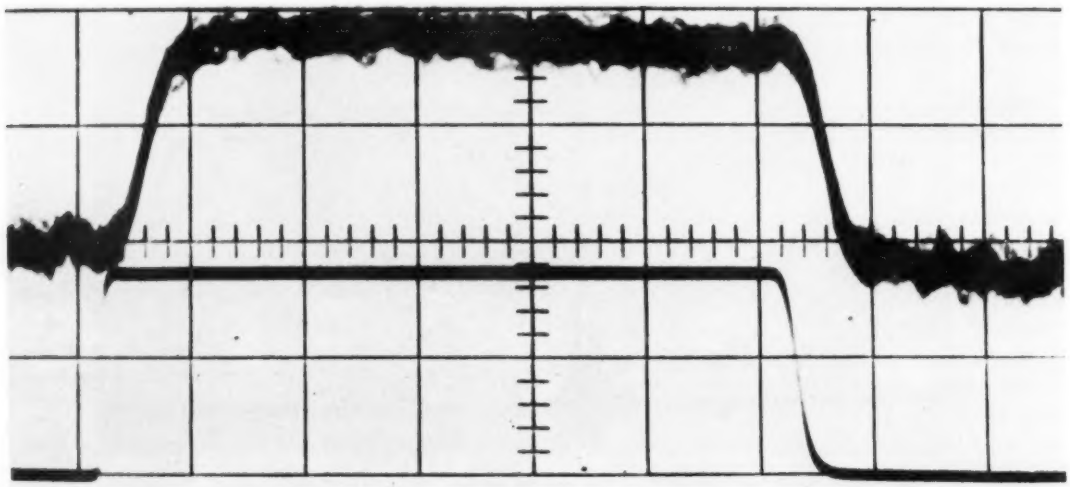

Figure 3. (Top) Oscillogram of the quasistatic voltage across a polished, 0.1-mm-thick, 2.8-mm-diameter, X-cut quartz disc which is caused by nonlinearities in the material coefficients associated with the longitudinal, coherent, overtone acoustic resonance. The rise time is 1 μ sec on the horizontal, 2 μ sec per division axis. The microwave power exciting the cavity is 1 w.
(Bottom) The microwave power to the cavity detected by a conventional semiconducting diode.

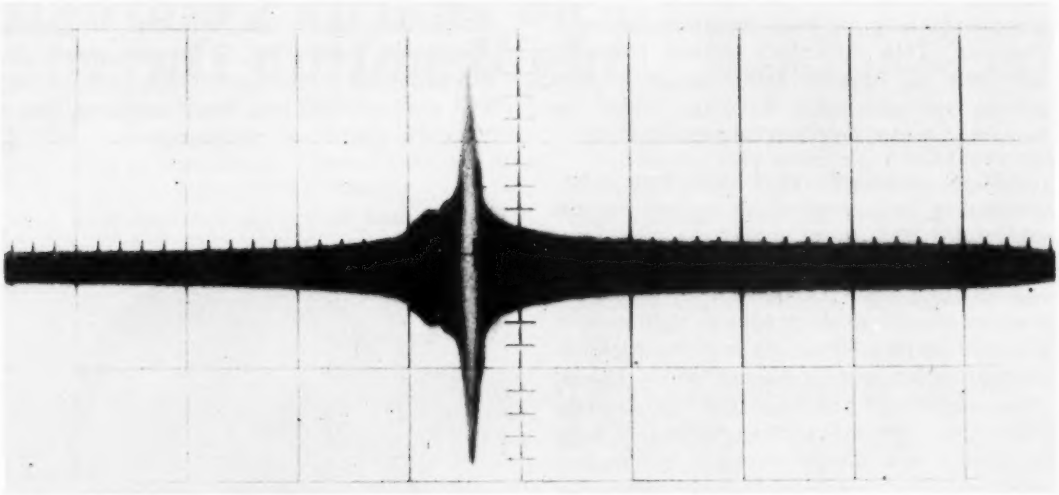

Figure 4. The peak-to-peak voltage (vertical scale) produced by the mixing in an X-cut quartz disc of two different microwave sources whose difference frequency is shown on the horizontal scale. The voltage maximum occurs when the difference frequency is equal to the 29-MHz fundamental acoustic-resonance frequency of the disc. The bandwidth at the half-power points is 16 kHz.

ORGANIC SOLAR CELLS

SPACE PHYSICS LABORATORY, AFCRL

The solar cells that cover certain satellites and their extendible collecting panels in a dark mirrored grid are inorganic semiconductors, their photoconducting material being silicon.

For the past several years, AFCRL has investigated the energy-converting properties of organic materials. This work, carried out under the direction of Dr. Aleksandar Golubovic, has resulted in significant advances in the efficiency of organic materials as energy sources. But the power output of present organic cells is well below that of conventional inorganic devices.

In certain applications, however, organic cells have distinct advantages. Most important of these is that they can be fabricated to respond to distinct wavelengths in the visible or near-infrared region. Extremely sensitive cells have been built with response times of microseconds. Thus they have potential application as sensors in research instrumentation. Other advantages are their low cost and weight and the fact that they can be fabricated in a variety of structural configurations. Primary disadvantages are high electrical resistance and a tendency to decompose under conditions of high temperatures or radiation fluxes.

Methods of fabricating organic and inorganic cells are similar. Both are based on the same physical principle. When an irradiated photoconductor is sandwiched between two different metallic electrodes, a photovoltage is generated. The internal con-

ducting mechanisms of the two types of semiconductors are fundamentally different, however. This difference arises from the fact that the organic semiconducting compounds are molecular crystals, while the inorganic compounds are valence-bonded.

AFCRL investigations involve both photoconductive and nonphotoconductive organic materials. With these materials, two types of thin-film cells are fabricated. The first and simpler type is formed by first depositing aluminum electrodes by high-vacuum sublimation on a Pyrex glass plate. A photoconductive organic compound and a second electrode of gold are deposited in turn on the aluminum electrode. The second type is fabricated in a similar manner, but instead of a single layer of photoconductive material, adjacent layers of photoconductive and nonphotoconductive materials are sandwiched between the aluminum and gold electrodes. (Figure 1 illustrates the general design for either type of organic cell.)

Golubovic has fabricated some 13 organic photovoltaic cells of both types, but with a range of different photoconductive and nonphotoconductive materials in various combinations. The two-layer system, in which the nonphotoconductive layer is an electron acceptor, has given the best power output in experiments to date.

Within the past year, Golubovic has steadily improved the power-output performance of organic devices; but considerably more work is needed before the potential of organic materials is fulfilled. At present, power has not exceeded three microwatts; photocurrent has not exceeded four microamperes, and is typically about one microampere.

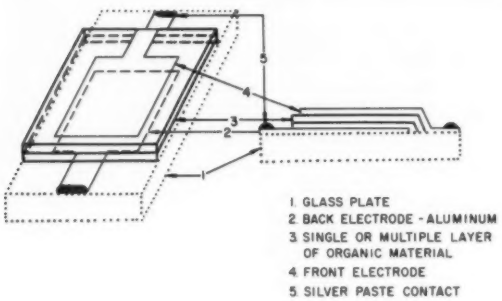
1. GLASS PLATE
2. BACK ELECTRODE - ALUMINUM
3. SINGLE OR MULTIPLE LAYER OF ORGANIC MATERIAL
4. FRONT ELECTRODE
5. SILVER PASTE CONTACT

Figure 1. Details of organic-cell design: (1) glass plate; (2) back electrode (aluminum); (3) single- or multiple-layered organic material; (4) front electrode; and (5) silver-paste contact.

Dr. Aleksandar Golubovic is a research chemist with the Quantum Processes Group, Energetics Branch, Space Physics Laboratory, AFCRL. He is currently studying and synthesizing new original organic photoconductors and semiconductors, making electrical measurements of photoconductive materials and conducting a basic study of the photoconductive properties versus structure of different photoconductive organic compounds, radical ions and free radicals.

Dr. Golubovic received a B. S. in Chemical Engineering from the University of Zagreb, Yugoslavia, in 1943, and a Ph. D. in Organic Chemistry from the same University in 1960. From July 1956 to June 1960 and from October 1960 to December 1962 he worked at the Massachusetts Institute of Technology as a Research Associate on the isolation, identification, and independent synthesis of organic peroxides, and developed new paper, column, and thin-layer chromatographic techniques for the isolation and identification of labile peroxides. From 1962 to 1964 Dr. Golubovic was Senior Scientist with Tyco Laboratories, Inc., Waltham, Mass. He is a member of the American Chemical Society.

lightning strikes on aircraft during flight

DR. ROBERT M. CUNNINGHAM
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The probable cause for several commercial aircraft crashes has been attributed to thunderstorm electricity--lightning. Lightning is a potential source of danger in all Air Force aircraft operations. Just how do lightning discharges to an aircraft affect the integrity of the aircraft, its instruments and its weapons systems?

To answer this question, AFCRL has conducted over the past several years a large experimental program involving three instrumented aircraft--a C-130, an F-100F, and a U-2. These aircraft have flown several hundred flights around, through and above

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Dr. Cunningham attended the Massachusetts Institute of Technology, from which he received his B. S. in 1942 and his Sc. D. in 1952. From 1942 to 1952 he was employed by M.I.T. first as a research assistant and instructor in meteorological instruments and synoptic meteorology; then as a research associate specializing in problems of aircraft deicing, instrumentation for measuring icing, and analysis of meteorology related to aircraft icing; and finally as a research associate in charge of the flight program and data analysis for the weather radar project.

lightning-producing thunderstorms. The object of this program is to determine the processes responsible for the formation of electrical-charge centers in convective clouds. Related objectives are to measure the current flow above thunderstorms and the relation of this current flow to the electrical charge of the earth, and to determine the relationship of electrically active portions of the storm to areas of turbulence and precipitation.

Most of the flights made during the period took place in Florida where electrical storms are frequent. The actual penetration flights were made with the F-100F. In 608 minutes of thunderstorm flight extending over several months, the aircraft was struck by lighting at least 33 times. On some of the flights, the lightning striking the aircraft was essentially the only lightning to occur during the penetration intervals, suggesting that the presence of the aircraft actually triggered the lightning stroke. Curiously enough, on other penetrations this triggering feature was not found. This suggests that some characteristic difference in storm properties may exist between different thunderstorms. The Laboratory is seeking to identify these differences and to explain why they occur.

Of the 33 lightning strikes encountered by the penetration aircraft, successful current measurements were accomplished on 24. Electrostatic-field fluctuations were measured for 27 of the strikes, and aircraft charge fluctuations were measured for 26.

The mean horizontal dimensions of continuous electrostatic-field disturbance were 36 km, with a standard deviation of 25 km. Maximum measurable electrostatic fields on the aircraft surface were up to 390,000 V/m. Sixty-nine percent of the strikes occurred when surface fields were less than 129,000 V/m.

The penetration flight data obtained by AFCRL permit construction of a lightning strike vs. altitude probability distribution curve for aircraft operation. The curve, when extrapolated to the ground, agrees well with surface measurements. This curve has also been extended upward to supersonic-transport altitudes using data from the U-2 aircraft taken during overflights of storms.

clear-air convective patterns

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During the summer, typically, the early morning sky is cloudless. Later in the morning cumulus clouds will form and will remain until late afternoon. What are the convective patterns that precede these clouds and follow their dissipation?

With the high-resolution radars operated by AFCRL at Wallops Island, Virginia, it is

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possible to observe these otherwise invisible convection patterns. Radar observation is possible because of the refractive structure of the air. AFCRL is using the radars to observe the clear-air convection patterns below 20,000 feet to determine their relationship to cloud formation.

The 3 powerful radars are operated at the wavelengths 3.2, 10.7 and 71.5 cm, respectively. By wavelength discrimination it is possible to distinguish between the backscattering from the clear-air refractive-index structure and the cloud returns due to backscattering from water droplets. The S-band (10.7 cm) radar is the most suitable radar for the study of clear-air returns, furnishing strong clear-air backscattering in combination with a high resolution. The S-band radar has a 3-Mw pulsed transmitter with a 60-foot dish giving a 3-db beamwidth of 0.5 degrees.

In the early morning, a thin horizontal clear-air layer near the surface is usually observed. Several thin stratified layers may be detected at higher altitudes. As surface heating continues, the surface layer rises and breaks up into convective patterns consisting of several convective cells with almost vertical boundaries. Simultaneously, the stratified layers at higher altitudes are broadened and intensified. As the convection continues, the moisture reaches saturation levels and clouds develop. The close connection between the clear-air convective patterns and the development of convective clouds is obvious.

In the afternoon, during the decaying stage of the convective process, the clouds dissipate but radar echoes are still observed in the region previously occupied by clouds. The decay of clear-air structures starts at the higher altitudes and proceeds to the lower levels. Convective patterns finally dissipate several hours after the visible clouds have vanished. The close connection between convective clouds and refractivity structures during the decaying stage suggests that the evaporation of cloud droplets and the creation of humidity gradients are important for the persistence of the clear-air patterns well after the convective forces are suppressed.

The clear-air convective cells preceding cloud formation are about 1 to 5 km in diameter, have maximum updraft speeds within their centers, and have lifetimes of at least 10 minutes. Usually, the cells are aligned with the wind but, on occasion, there is evidence that a group of cells will form around the circumference of a circle whose diameter is on the order of 10 km.

In a related study, a Lane refractometer was installed in a helicopter performing ascending and descending spirals as well as porpoising and constant-altitude runs. The helicopter position was compared with the location of refractivity data on radar displays. A one-to-one correspondence between main refractivity disturbances and clear-air returns was revealed.

NIGHT VISIBILITY

UPPER ATMOSPHERE PHYSICS LABORATORY, AFCRL

The Air Force, Army and Navy have all put a great deal of effort into research on devices that will enable an observer to "see" at low light levels with greater efficiency. Scores of electronic image intensifiers, solid-state image converters, and optical systems have been developed by the military and by private concerns. Many of these devices are 10,000 times more sensitive than the fastest photographic emulsions and can "see" at much lower luminance levels than the human eye.

All have various limitations for Air Force application because of complexity, weight, image distortion, resolving power, slow scanning rates, and limited life of the components. In an AFCRL report, "Some Aspects of Night Visibility Useful for Air Force Operations" (AFCRL-66-862), Dr. Sam M. Silverman of AFCRL and J. B. Taylor of HRB-Singer, re-

view several light intensifiers that have been developed, and comment on their effectiveness. In their survey report, the authors also discuss the relative intensities of nighttime light sources--full moon, zodiacal light, night airglow, stars, and so on--as well as the psychophysical aspects of vision itself.

A difficulty facing the authors--or anyone undertaking such a study--is that of establishing some common figure of merit. Under at least one type of analysis, known as the "detective quantum efficiency," the performance of the human eye exceeds that of any of the instruments developed. The detective quantum efficiency is a concept to establish the speed of any system in absolute terms. The light-adapted eye can resolve objects speedily over a wide range of luminance levels ranging from bright sunlight with 10,000 lumens per square foot to the landscape in moonlight at only about 1/1000 lumen per square foot.

The authors note that the ability to distinguish objects at night depends on both physical and psychophysical factors. These fall into three groups:

a) Properties of the source of illumination, including its intensity as a function of wavelength and its geographical and temporal variations.

b) Characteristics of the object illuminated--in particular, its spectral reflectance as a function of wavelength and its degree of self-luminosity, if any, in one or more regions of the spectrum.

c) Characteristics of the sensing instrument--be it eye, photographic plate, or television tube. Properties such as its response as a function of wavelength, sensitivity and threshold values are important here.

Examined in the report are a number of image converters and intensifiers developed during the past 10 years, some using scanning techniques. Most of these devices have been designed for such applications as astrophotography, X-ray and fluoroscopic enhancement, video recording, and the recording of particle tracks in scintillation crystals and bubble chambers. Also examined were systems that do not use visible light, such as active and passive infrared systems.

While all the systems examined were useful for certain specific applications, very few approached the authors' criteria for an optimum general system. They note that this ideal system must enhance the threshold response of the dark-adapted eye, and do it in real time, with angular resolution as good as that of the eye. At the same time the system should be simple, compact and relatively light in weight. ✪

Dr. Sam M. Silverman is a supervisory research physicist and Chief of the Aurora and Airglow Branch, Upper Atmosphere Physics Laboratory, AFCRL. He has been with AFCRL since 1957, working primarily in the fields of auroral and airflow physics. He has the degree of B.Ch.E. from the College of the City of New York (1945), and a Ph.D. degree from the Ohio State University (1952). After receiving his Ph.D., he remained at O.S.U. until January 1955 as a research associate. Following that, he became Assistant Professor of Chemical Physics at the Institute of Silicate Research, University of Toledo. Dr. Silverman is a member of the American Physical Society, Sigma Xi, the American Physical Union, and RESA.

solar flare of May 23, 1967

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On May 23, 1967, a solar flare of enormous energy was observed by AFCRL radio astronomers. The flare was the third largest in terms of energy ever observed by radio telescopes. It started at 1809 U.T. (1309 EST) and lasted for several hours.

The flare came from an active region on the sun which had already produced several previous flares. One flare on May 21st had been observable in white light; in the history of astronomy only about a dozen flares have been observed without the normal H alpha filter. The May 23rd flare was situated very close to the center of the sun, thus insuring that a flare of its magnitude would have considerable effect on the earth's magnetic field.

This May 23rd flare was observed at AFCRL's Sagamore Hill Solar Radio Observatory, Hamilton, Mass., with 2 antennas tuned to 5 frequencies. The complete time history was also observed at 35 GHz by an 8-foot solar radio telescope located at the main AFCRL Laboratories in Bedford, Mass. This is the first time that the complete time history of such a large proton event has been observed at a frequency of 35 GHz. The research group at AFCRL immediately predicted that the flare would produce high-energy protons.

Protons were indeed observed 4 hours later. The protons are high-energy particles of about 10 to 50 million electron volts which ionize a region over the North Pole (the polar cap). The energy of these particles produces electrons which almost eliminate normal communications over the polar-cap region.

The increased velocity and number of particles in the solar wind produced a severe magnetic storm. This appeared at 1019 U.T. on May 25th, about 40 hours after the start of the flare. The magnetic storm and the high proton flux were observed for approximately 80 hours after the solar-flare event.

Dr. Jules Aarons is Senior Scientist and Chief, Radio Astronomy Branch, Space Physics Laboratory, AFCRL. His current work includes studies in radio star and satellite scintillation at various latitudes as well as observations of the Early Bird synchronous satellite. He is co-ordinator of the Joint Satellite Studies Group, an international group of observatories engaged in a satellite beacon program. In addition, he is directly concerned with studies of microwave radiation from the sun.

Dr. Aarons received a B. S. in Education from the City College of New York (1942), an M. S. in Physics from Boston University (1950), and a Ph. D. in Geophysics from the University of Paris (1954). He is a member of the American Geophysical Union, the American Astronomical Society, the Institute of Electrical and Electronic Engineers, and the American Association for the Advancement of Science, and is also a fellow of the Royal Astronomical Society. He serves on Commissions 3 (Ionospheric Radio) and 5 (Radio and Radar Astronomy) of the International Scientific Radio Union, and on Commission 5 (Solar Terrestrial Relationships) of the International Union of Geodesy and Geophysics and the International Association of Geomagnetics and Aeronomy.

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